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Prediction of Diameter, Weight and Quality of Apple Fruit (*Malus domestica* Borkh.) cv. 'Elstar' using Climatic Variables and their Interactions

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Summary

The objective of the present work was to determine the relationship between fruit size, fruit weight, fruit quality and climate factors and the interaction of these factors at harvest in order to predict the optimal harvest date to obtain high quality apples after storage.

The first evaluation of 'Elstar' apples, included weekly determination of apple diameter and the second evaluation included at harvest measurement of fruit weight and fruit quality (Streif index). All apples were cold-stored in normal atmosphere at 3 °C or in low oxygen atmosphere at 1 °C immediately after picking. Analytical data were combined with daily registered meteorological data including: the sums of degree days, rainfall in the morning including minimum precipitation and/or dew, maximum precipitation (rainfall), evaporation potential, wind velocity, average daily relative humidity, vapour pressure deficit, global radiation, soil temperature and surface wetness. Factor analyses identified three non-correlated factors; 1) energy and water, 2) heat and wind and 3) vapour deficit. The factor loadings were used to determine the importance of each climate variable and its interactions on characteristics of the apple fruit. Multiple regression analyses, with forward selection of climate variables or their interactions showed that apple fruit diameter was significantly affected by two climate factors: 1) degree days and 2) evaporation potential. Only degree day had a significant effect on apple fruit weight. Fruit quality (Streif index) was affected by two climate factors: 1) degree days and 2) relative humidity. Apple fruit diameter, fruit weight and fruit quality were modelled using climate. The differences between measured and predicted diameter, weight and fruit quality were 0.2 mm, 1 g and 0.09 kg cm^{-2} $ww\%^{-1}$ $scores^{-1}$, respectively. In view of climate change with expected warmer temperatures, the value establishing and using statistical models for prediction of quality characteristics will increase considerably.

Key words. climate factors – diameter – factor analysis – modelling – fruit quality – weight

Introduction

An ability to predict apple fruit growth and quality characteristics would make it possible to take informed decisions on fruit thinning, fruit size and fruit yield (Stajnko et al. 2009), planning of harvest labour and determination of the optimum harvest time and storage conditions, which would increase the profitability of apple fruit production.

The most successful prediction of the optimum harvest date for apples is based on heat accumulation, calculated as the sum of the daily minimum and the maximum temperature from the date of full flowering to harvest (Streif 1983, 1996; Perry et al. 1987; Stanley et al. 2000). Streif index is one assessment of apple fruit quality characteristics for determination of the optimum maturity for long storage of apples (De Jäger and Roelofs 1996; Streif 1996). Research has shown that a simple set of equations, including one or a few climate variables, may be applicable for prediction of essential fruit characteristics before harvest and storage (Perry et al. 1987; Atkinson et al. 1995). However, the effects of several climate factors and their interactions have not previously been evaluated using multiple regression analysis with forward selection of climate factors.

As all climate variables, measured in the most apple producing countries, may affect growth and quality of apple fruit it was hypothesized that accumulated values of additional climate variables and their interactions could be useful for predicting the optimum harvest time based on apple fruit diameter, weight and the fruit quality. In most European countries, the optimum harvest date is presently determined by referencing the number of days between T-stage and harvest (Stajnko et al. 2009). Several Gompertz and Chanter equations, sigmoid functions (Thornley and Johnson 1990) and multiple linear functions (Narasimham et al. 1988; Bergh and Cloete 1992) have been used for predicting optimum harvest time for apples without a preliminary comparative analysis of the importance of climate factors. This may be possible using a factor analysis.

Therefore, the aim of this research was to evaluate the importance of climate variables and their interactions in

predicting apple fruit diameter, fruit weight and fruit quality in the period from full bloom to harvest. The outcome of this research was to determine the optimum picking date in order to improve storability and quality characteristics of apple fruit.

Materials and Methods

Apple trees

Apple trees of the cultivar 'Elstar' grafted on rootstock M9 were established on sandy loam (JB6) in 1989/1990 at an experimental area situated at (10° 27' (E), 55° 18' (N)) around 10 km south of the city Odense close to the centre of the island Fuenen, Denmark. The planting distance was 3.75 x 1.75 m and the trees were fertilised using 100 kg ha^{-1} potassium in early spring and 50 kg ha^{-1} nitrogen in late spring. The soil was very rich in phosphorus and calcium. Pesticides and herbicides were used according to the recommendations for integrated production. Thinning of flowers and fruits were carried out using ammonium thiosulphate at flowering and completed by hand thinning.

Sampling of apples

Assessment one (2002 to 2005), date of full bloom was determined and 100 apples were randomly selected each year from 10 trees and fruit diameters were measured weekly for 16–18 weeks until harvest.

At harvest 50 to 100 apples were picked randomly from the 10 trees at 6–7 days around the expected optimum harvest time and fruit weight and fruit quality were measured. Fruit were stored at 3 °C for up to 64 d and single fruit weight, soluble solids, starch index and fruit quality (Streif index) were determined several times during storage. The data from 2002 to 2004 were used to model statistical equations for prediction of apple fruit diameter, fruit weight and fruit quality and the data from 2005 were used to validate these equations.

Storage

Assessment two (2005), 230 apples were randomly sampled from the same 'Elstar' orchard as used in assessment one, and fruit were stored at 1 °C in two 120 L tightly closed cylinders with an atmosphere of 1.5/1.5 % O_2/CO_2 for up to 204 d for physical and chemical analyses.

Meteorological data

Meteorological data from the five growing seasons, from full bloom to harvest, were obtained from the weather station owned by Danish Meteorological Institute based at the experimental station (location: 10° 27' (E) 55° 18' (N). The data collected included global radiation, MJ m^{-2}; degree days, °C calculated as the average of daily minimum (Tmin) and maximum temperatures (Tmax), without using a base temperature; precipitation in the morning, mm at 1.5 m at 08:00; maximum precipitation, mm; average of minimum and maximum daily relative humidity, %; surface wetness, min; evaporation potential, mm; soil temperature at 30 cm depth, °C; vapour pressure deficit, kPa and wind velocity at 10 m s^{-1}.

Physical and chemical analyses

Apple fruit diameter was measured using a calliper gauge, and fruit weight was determined and recorded using a Sartorius weight (BP 310 S, Bie and Berntsen, Roedovre, Denmark) or an acoustic firmness sensor equipped with a gauge and a scale (Aweta B.V., Burgemeester, Nootdorp, The Netherlands). A very thin slice (~1 mm) of the apple fruit skin was removed from the equatorial part of the most mature half of each apple before determination of firmness (kg cm^{-2}) using a penetrometer (Effegi, FT 327, Milan, Italy) equipped with an 11 mm plunger and a sample of fruit liquid was taken from the hole produced by the plunger and used for determination of soluble solids (w/w %) using a refractometer (Bellingham + Stanley, RF M 800, Turnbridge Wells, Kent, UK). Finally a thick equatorial slice (1 cm) was cut from each apple and dipped in potassium iodine (KJ 10 g L^{-1}, J.T. Baker no 1118) and iodine (J_2 3 g L^{-1}, Merck Art. 105043) for 1 min at 20 °C to determine the starch content. Starch index was determined visually using a scale of 0–10, where a starch index of 0 represented a completely dark blue apple area and a starch index of 10 represented no dark blue area. The fruit quality (kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$) was calculated based on the methods described previously (De Jäger and Roelofs 1996; Streif 1996).

The average of apple fruit diameter, weight and fruit quality measured in assessment one and two included 77 sums of the 10 climate variables (2002–2004) at 15 weekly intervals and at harvest of apples at 6 dates approximating expected optimum harvest time (2005).

Statistical analysis

The statistical analyses of normalised data included a classical factor analysis, analysis of variance (ANOVA), linear regression, and multiple regressions with forward selection of climate variables (Statistical Graphics Corporation, Version 4, Rockville, USA). The classical factor analyses included varimax rotation as described by Überla (1971) and Sharma (1996).

The data from analysis of apples harvested in 2002, 2003 and 2004 were used for statistical modelling of relationships between apple fruit diameter, weight and fruit quality using meteorological data from 2002, 2003 and 2004 and the data obtained in 2005 were used for validation of the developed statistical models. Factor loadings were considered significant by the value 0.60.

Results

The sums of degree days, precipitations, wind velocity, relative humidity, vapour pressure deficit and surface wetness varied considerably, whereas less variation was found for evaporation potential, global radiation and soil temperature (Table 1).

Variation in quality characteristics

Over the four experimental years, full bloom occurred 16 to 20 May and the fruit diameter measuring started 11 to 46 d after full bloom were harvested 131 to 137 d after full bloom. Apple fruit diameter increased from 5.4 to

Table 1. Sum of climate variables during the fruit growth period, from full bloom to harvest, 2002–2005 using data from the Danish Meteorological Institute.

Year[1]	Full bloom date	Finally harvest date	Degree days (°C)	Precipitation 08:00 (mm)	Maximum precipitation (mm)	Evaporation potential (mm)	Wind velocity (m s^{-1})	Relative humidity (%)	Vapour deficit (kPa)	Global radiation (MJ m^{-2})	Soil temperature at 30 cm depth (°C)	Surface wetness (min)
2002	30. May	30. Sep	2243	233	235	417	457	9996	24	2282	2136	54185
2003	29. June	30. Sep	1886	213	435	439	574	7740	24	2228	2086	53168
2004	01. July	21. Sep	2188	300	306	420	611	12444	54	2420	2199	60498
2005	19. May	04. Oct	2116	261	261	407	475	11114	54	2286	2094	61454
Average			2108	252	309	421	529	10324	39	2304	2129	57326

[1]Sampling and analyses of apples and statistical modelling in 2002, 2003, 2004 and validation of the statistical models 2005.

Table 2. Average of fruit diameter, fruit weight and fruit quality (Streif index) at harvest (2002–2004).

Variable	Diameter (mm)	Fruit weight (g)	Fruit quality (kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$)
Average	76.2	150	0.24
Minimum	5.4	62	0.03
Maximum	86.7	265	1.30
Standard deviation	18.6	32	0.32
Coefficient of variance	24.4	21	133
Number of measurements	4357		
Number of apples		2874	2024

Table 3. Fruit quality (Streif index) after normal atmosphere cold storage of apples at 3 °C and low oxygen storage 1.5/1.5 % O_2/CO_2 at 1 °C in 2004/2005.

Days in cold storage at 3 °C	Streif index (kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$)	Days in CA storage at 1 °C	Streif index (kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$)
1	0.45 a[1]	1	0.52 a
32	0.05 b	5	0.24 b
64	0.04 b	7	0.11 c
		88	0.06 d
		151	0.05 d
		204	0.05 d

[1]Different letters denote a significant difference in a column $P < 0.05$.

76.9 mm in 2002, from 25.1 to 75.3 mm in 2003, and from 30.6 to 76.5 mm in 2004.

The average and distribution of the data used for development of statistical models varied considerably between years. The differences between maximum and minimum at harvest for fruit weight and fruit quality were 4 mm, 203 g and 1.27 kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$, respectively (Table 2).

Cold storage of 'Elstar' apples in normal atmosphere 3 °C for up to 64 d and in low oxygen atmosphere with 1.5/1.5 % O_2/CO_2 at 1 °C (Ca storage) for up to 204 d, resulted in a significant decrease in the fruit quality to 0.05 kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$ after 32 d in normal atmosphere storage at 3 °C and after 151 d in CA storage (Table 3).

Apple fruit quality factors and their loadings

The factor analysis identified: 1) energy and water factor, 2) heat and wind factor and 3) vapour deficit factor, with eigenvalues 27.2, 19.5 and 3.9, respectively, which attributed to 47, 34 and 7 % of the data variation, respectively. The size of the factor loadings from the climate variables on the energy and water factor, heat and wind factor and on the vapour deficit factor varied from −0.96 to 0.99, −0.19 to 0.97 and from −0.27 to 0.94, respectively (Table 4).

Energy and water factor

Three quality characteristics (fruit diameter, fruit weight and fruit quality), seven major climate variables (degree days, global radiation, evaporation potential, precipitation in the morning, maximum precipitation, relative humidity, surface wetness) and 19 interactions had a significant impact on the energy and water factor. Soil temperature, wind velocity and vapour pressure deficit and 26 interactions had no significant impact on the energy and water factor (Table 4).

Heat and energy factor

The heat and wind factor had significant loadings above 0.96 from soil temperature and wind velocity, whereas the loadings varied from 0.60 to 0.96 for 16 interactions including degree days*soil temperature at 30 cm depth,

Table 4. Sorted factor loadings from the climate variables on the three statistical factors (n = 77).

Variable[1]	Name of statistical factor 1, 2 and 3		
	Energy and water	Heat and wind	Vapour pressure deficit
Diameter	0.96	−0.11	0.01
Weight	0.94	0.14	0.06
Fruit quality (Streif index)	−0.96	−0.06	−0.03
Degree days	0.97	−0.06	−0.03
Degree days*global radiation	0.97	0.01	0.19
Degree days*evaporation potential	0.96	0.06	0.22
Degree days*precipitation in the morning	0.96	−0.12	−0.10
Degree days*maximum precipitation	0.79	0.50	0.27
Degree days*relative humidity	0.97	−0.13	0.08
Degree days*surface wetness	0.69	0.10	−0.22
Global radiation	0.98	−0.02	−0.06
Evaporation potential	0.97	0.07	−0.03
Evaporation potential*global radiation	0.96	0.10	0.17
Evaporation potential*relative humidity	0.98	−0.06	0.05
Evaporation potential*surface wetness	0.97	0.13	0.15
Precipitation in the morning	0.95	−0.07	−0.08
Precipitation in the morning*global radiation	0.99	−0.06	0.00
Precipitation in the morning*evaporation potential	0.79	0.57	0.17
Precipitation in the morning*maximum precipitation	0.86	0.42	0.11
Precipitation in the morning*relative humidity	0.96	−0.17	−0.10
Precipitation in the morning*surface wetness	0.99	−0.03	−0.01
Maximum precipitation	0.69	0.66	0.10
Maximum precipitation*global radiation	0.85	0.50	0.12
Maximum precipitation*evaporation potential	0.81	0.56	0.15
Maximum precipitation*relative humidity	0.95	0.28	0.00
Maximum precipitation*surface wetness	0.85	0.50	0.11
Relative humidity	0.96	−0.18	−0.18
Relative humidity*global radiation	0.94	−0.09	0.09
Surface wetness	0.98	0.04	−0.06
Global radiation*surface wetness	0.56	−0.09	−0.27
Soil temperature*surface wetness	0.56	−0.19	−0.22
Degree days*soil temperature	0.03	0.88	0.21
Degree days*wind velocity	0.08	0.95	0.25
Global radiation*soil temperature	−0.06	0.74	0.16
Evaporation potential*soil temperature	0.06	0.95	0.25
Evaporation potential*wind velocity	0.06	0.96	0.24
Precipitation in the morning*soil temperature	0.06	0.96	0.23
Precipitation in the morning*wind velocity	0.07	0.96	0.23
Maximum precipitation*soil temperature	0.04	0.96	0.24
Maximum precipitation*vapour pressure deficit	0.04	0.70	0.70
Maximum precipitation*wind velocity	0.04	0.96	0.24
Relative humidity*soil temperature	0.08	0.53	0.03
Soil temperature	−0.05	0.97	0.21
Vapour pressure deficit*soil temperature	−0.14	0.74	0.21
Wind velocity	−0.06	0.97	0.19
Wind velocity*global radiation	0.07	0.95	0.24
Wind velocity*relative humidity	0.08	0.96	0.24
Wind velocity*surface wetness	0.20	0.63	0.05
Wind velocity*soil temperature	−0.22	0.78	0.08
Wind velocity*vapour pressure deficit	0.00	0.95	0.28
Degree days*vapour pressure deficit	0.10	0.36	0.92
Evaporation potential*vapour pressure deficit	0.06	0.44	0.89

Table 4. Continued

Variable[1]	Name of statistical factor 1, 2 and 3		
	Energy and water	Heat and wind	Vapour pressure deficit
Precipitation in the morning*vapour pressure deficit	0.07	0.36	0.92
Relative humidity*surface wetness	0.12	−0.10	0.03
Relative humidity*vapour pressure deficit	0.08	0.30	0.94
Vapour pressure deficit	−0.18	0.41	0.88
Vapour pressure deficit*global radiation	0.07	0.41	0.90
Vapour pressure deficit*surface wetness	−0.13	0.31	0.64

[1]Degree days, °C; global radiation, MJ m^{-2}; evaporation potential, mm; maximum precipitation, mm; precipitation at 1.5 m at 8:00. precipitation in the morning, mm; relative humidity, %; surface wetness, min; soil temperature in 30 cm depth, °C; vapour pressure deficit, kPa; wind velocity at 10 m, m s^{-1}.

degree days*wind velocity, global radiation*soil temperature at 30 cm depth, evaporation potential*soil temperature at 30 cm depth, evaporation potential*wind velocity, precipitation in the morning*soil temperature at 30 cm depth, precipitation in the morning*wind velocity, maximum precipitation*soil temperature at 30 cm depth, maximum precipitation*vapour pressure deficit maximum precipitation*wind velocity, vapour pressure deficit*soil temperature in 30 cm depth, wind velocity*global radiation, wind velocity*relative humidity, wind velocity*surface wetness, wind velocity*soil temperature in 30 cm depth, and wind velocity*vapour pressure deficit (Table 4). However, these 18 climate variables were not correlated with diameter, weight or fruit quality (Table 4).

Vapour pressure deficit factor

The climate variables that had a significant impact on the vapour pressure deficit factor were vapour pressure deficit and six interactions with loadings from 0.64 to 0.94 (including degree days*vapour pressure deficit, evaporation potential*vapour pressure deficit, precipitation in the morning*vapour pressure deficit, relative humidity*vapour pressure deficit, vapour pressure deficit*global radiation and vapour pressure deficit*surface wetness). None of these climate variables were significantly correlated to apple fruit diameter, weight or fruit quality.

Effects of climate variables

Simple linear regression analysis using s-functions (y = exp(a + b/x)) where y is fruit diameter and x is the climate variable showed that degree days, evaporation potential, relative humidity, global radiation and surface wetness, resulted in more than 90 % data inclusion (Table 5). Regression of the other climate factors including precipitation in the morning at 08.00, maximum wind velocity, and soil temperature resulted in non-satisfactory inclusion of data variation from 54 to 61 % and none inclusion using vapour pressure deficit. Data inclusion by regression of fruit diameter versus the 45 interactions varied from 1 to 77 %, these are non-satisfactory in relation to prediction of optimum harvest time using these climate variables.

Regression of fruit weight versus degree days, evaporation potential, relative humidity, global radiation and surface wetness using linear equations (y = a + bx) was above 93 %. Whereas regression of fruit weight versus the other climate factors and the 45 interactions between climate variables was considered non-satisfactory with variations from 0 to 89 % (Table 5).

Above 94 % inclusion of data variation was obtained by regression of fruit quality versus degree days, evaporation potential, global radiation and surface wetness, whereas regression of the remaining major variables and interactions resulted in non-satisfactory relationships with data inclusion from 0 to 85 % (Table 5).

Multiple regressions with forward selection of climate variables (F = 4.00; P< 0.05) resulted in three models of: 1) fruit diameter, 2) fruit weight and 3) fruit quality with 98.1, 96.9 and 99.3 %, respectively:

Log_{10} fruit diameter = 0.7 + 7.3E-4 maximum precipitation + degree days (2.5E-6 maximum precipitation − 2.2E-6 precipitation in the morning) + evaporation potential (5.9E-3 − 1.5E-5 precipitation in the morning) + 6.6E-8 surface wetness*precipitation in the morning − global radiation (4.5E-10 surface wetness − 2.0E-7 degree days) (Equation 1)

Weight = −19.1 + 0.0829 degree days (Equation 2)

Fruit quality = 2.85 + wiv(8.4E-8 relative humidity − 8.0E-7 maximum precipitation − 1.5E-7 global radiation − 9.8E-4 degree days − 5.8E-5 relative humidity (Equation 3)

Apple fruit diameter was significantly dependent on maximum precipitation, evaporation potential, degree days*maximum precipitation, degree days*precipitation in the morning, evaporation potential*precipitation in the morning, surface wetness*precipitation in the morning, global radiation*surface wetness, and global radiation*degree days (Equation 1), whereas fruit weight was only significantly dependent on degree days (Equation 2). Fruit quality was significantly dependent on degree days, relative humidity, wind velocity*relative humidity, wind velocity*maximum on precipitation and wind velocity*global radiation (Equation 3).

Table 5. Results from regression of apple fruit diameter, fruit weight and fruit quality (Streif index) versus 77 climate sums for 'Elstar' apples.

Variable	Constant (diameter)	Regression coeff.*E+5 (diameter)	R^2 (%)	P^2	Constant (weight)	Regression coeff.*E+5 (weight)	R^2 (%)	P	Constant (Fruit quality)	Regression coeff.*E+5 (Fruit quality)	R^2 (%)	P
[1]Degree days	4.6	−624.5	96	***	−19.1	8288.1	97	***	2.8	−120.14	96	***
Degree days*precipitation in the morning	4.1	3409.4	51	***	28.8	24.7	89	***	2.1	−0.35	85	***
Degree days*maximum precipitation	4.1	−3058.3	48	***	50.3	19.0	46	***	1.9	−0.31	59	***
Degree days*evaporation potential	4.2	−35923.9	75	***	21.9	19.2	80	***	2.2	−0.28	82	***
Degree days*wind velocity	4.2	−36445.9	61	***	110.4	0.013	0	ns.	1.0	−0.0030	3	ns.
Degree days*relative humidity	4.2	−737069.0	76	***	30.0	0.73	80	***	2.0	−0.010	76	***
Degree days*vapour pressure deficit	4.1	−3915.2	3	ns.	108.6	0.20	0	ns.	1.0	−0.0066	2	ns.
Degree days*global radiation	4.2	−204068.0	77	***	22.2	3.5	81	***	2.2	−0.051	81	***
Degree days*soil temperature	4.1	−118444.0	61	***	111.1	−0.0043	0	ns.	0.9	−0.00057	2	ns.
Degree days*surface wetness	4.2	−3254240.0	69	***	50.5	0.12	51	***	1.8	−0.0019	56	***
Precipitation in the morning	4.2	−14.9	60	***	−11.1	64973.9	79	***	2.6	934.8	77	***
Precipitation in the morning*maximum precipitation	4.1	−74.5	42	***	38.1	174.7	55	***	2.0	2.8	66	***
Precipitation in the morning*evaporation potential	4.1	−713.4	47	***	43.6	94.4	50	***	2.0	−1.6	65	***
Precipitation in the morning*wind velocity	4.1	−869.8	47	***	110.8	−0.038	0	ns.	1.0	−0.023	3	ns.
Precipitation in the morning*relative humidity	4.1	−16623.7	51	***	29.9	5.5	81	***	2.0	−0.077	75	ns.
Precipitation in the morning*vapour pressure deficit	4.1	−1069.0	9	**	109.5	0.9	0	ns.	0.9	−0.046	1	***
Precipitation in the morning*global radiation	4.1	−4594.9	50	***	17.2	27.7	86	***	2.2	−0.40	84	***
Precipitation in the morning*soil temperature	4.1	−2806.1	47	***	110.7	−0.0023	0	ns.	1.0	−0.0048	3	ns.
Precipitation in the morning*surface wetness	4.1	−77135.6	51	***	25.0	1.13	85	***	2.1	−0.0163	84	***
Maximum precipitation	4.2	−13.2	56	***	33.2	35245.9	37	***	2.2	−613.6	53	***
Maximum precipitation*evaporation potential	4.1	−713.6	47	***	40.6	96.8	54	***	2.0	−1.60	69	***
Maximum precipitation*wind velocity	4.1	−795.4	46	***	111.3	−0.13	0	ns.	0.9	−0.0098	2	ns.
Maximum precipitation*relative humidity	4.1	−14957.3	48	***	25.7	5.0	75	***	2.2	−0.078	84	ns.
Maximum precipitation*vapour pressure deficit	4.1	−1112.6	10	*	110.9	−0.15	0	ns.	0.9	−0.033	2	ns.
Maximum precipitation*global radiation	4.1	−4121.6	48	***	35.5	19.0	59	***	2.1	−0.31	74	***
Maximum precipitation*soil temperature	4.1	−2565.9	46	***	111.2	0.021	0	ns.	0.9	−0.0020	2	ns.
Maximum precipitation*surface wetness	4.1	−69658.1	49	***	41.0	0.78	60	***	2.0	−0.013	74	***
Evaporation potential	4.6	−161.2	94	***	−42.4	47655.7	95	***	3.1	−703.63	97	***
Evaporation potential*wind velocity	4.2	−8517.7	59	***	110.8	−0.034	0	ns.	0.9	−0.012	3	ns.
Evaporation potential*relative humidity	4.2	−174141.0	74	***	23.1	3.8	82	***	2.1	−0.055	79	***
Evaporation potential*vapour pressure deficit	4.1	−730.7	2	***	109.8	0.40	0	ns.	0.9	−0.027	1	ns.
Evaporation potential*global radiation	4.2	−48417.1	74	***	16.6	17.7	80	***	2.3	−0.26	83	***
Evaporation potential*soil temperature	4.2	−27717.1	59	***	110.7	−0.0028	0	ns.	0.9	−0.0024	3	***
Evaporation potential*surface wetness	4.2	−810036.0	74	***	24.6	0.72	80	***	2.2	−0.011	84	***

Table 5. Continued

Variable	Constant (diameter)	Regression coeff.*E+5 (diameter)	R^2 (%)	P[2]	Constant (weight)	Regression coeff.*E+5 (weight)	R^2 (%)	P	Constant (Fruit quality)	Regression coeff.*E+5 (Fruit quality)	R^2 (%)	P
Wind velocity	4.3	−122.5	54	***	114.4	−217.4	1	ns.	0.9	−1.15	0	ns.
Wind velocity*relative humidity	4.2	−176183.0	60	***	110.4	0.0030	0	ns.	1.0	−0.00073	3	ns.
Wind velocity*vapour pressure deficit	4.1	−596.6	1	ns.	112.0	−0.050	0	ns.	0.9	−0.0013	1	ns.
Wind velocity*global radiation	4.2	−48863.5	59	***	110.6	0.0029	0	ns.	1.0	−0.0024	3	ns.
Wind velocity*soil temperature	4.1	−30780.5	59	***	116.9	−0.075	7	ns.	0.8	0.00064	2	ns.
Wind velocity*surface wetness	4.2	−827983.0	62	***	102.4	0.043	2	ns.	1.1	−0.0010	4	ns.
Relative humidity	4.6	−3002.9	91	***	5.7	−6902339	95	***	2.6	−22.2	83	***
Relative humidity*vapour pressure deficit	4.1	−17840.1	2	ns.	4.5	−1577590000	0	ns.	0.9	−0.0013	1	ns.
Relative humidity*global radiation	4.2	−989805.0	76	***	4.2	−98980500000	76	***	2.1	−0.0097	70	***
Relative humidity*soil temperature	4.2	−57316.0	60	***	4.2	−57531600000	60	***	0.9	−0.00037	1	ns.
Relative humidity*surface wetness	4.3	−8444080.0	24	***	104.7	0.016	0	ns.	0.9	−0.000085	0	ns.
Vapour pressure deficit	4.0	1.4	0	ns.	119.4	1202.1	4	ns.	0.8	10.3	1	ns.
Vapour pressure deficit*global radiation	4.1	−5028.7	2	ns.	109.5	0.10	0	ns.	0.9	−0.0053	1	ns.
Vapour pressure deficit*soil temperature	4.1	−4358.1	3	ns.	114.0	−0.039	2	ns.	0.9	0.000029	0	ns.
Vapour pressure deficit*surface wetness	4.1	−108924.0	4	ns.	115.5	−0.028	2	ns.	0.9	0.00016	0	ns.
Global radiation	4.6	−859.2	93	***	−37.9	8403.4	95	***	3.1	−122.9	95	***
Global radiation*soil temperature	4.2	−159191.0	59	***	112.9	−0.024	1	ns.	0.9	−0.00029	0	ns.
Global radiation*surface wetness	4.2	−4044010.0	59	***	58.6	0.10	41	***	1.7	−0.0015	43	***
Soil temperature	4.3	−425.9	61	***	113.8	−39.0	1	ns.	0.9	−0.31	0	ns.
Soil temperature*surface wetness	4.2	−2647710.0	59	***	59.0	0.11	37	***	1.6	−0.0015	30	***
Surface wetness	4.5	−14167.5	96	***	−14.2	317.4	94	***	2.7	−4.7	99	***

[1]Degree days, °C (no reference temperature); global radiation, MJ m^{-2}; evaporation potential, mm; maximum precipitation, mm; precipitation at 1.5 m at 8:00 pm, mm; relative humidity, %; surface wetness, min; soil temperature in 30 cm depth, °C; vapour pressure deficit, kPa; wind velocity at 10 m, m s^{-1}.
[2]Significance: *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$; ns: not significant.

Validation of the prediction equations

Results from determination of measured fruit diameter, fruit weight and fruit quality in 2005 and the predicted values of these characteristics obtained using the three equations (models) presented above using experimental data from 2002 to 2004 are presented in Table 6. The differences between measured and modelled apple fruit diameters using degree days varied from −1.7 to 0.8 with a minimum of 0.2 mm at harvest on 27 September. The differences between measured and predicted fruit weight values varied from 0 to 6 g and for fruit quality values varied from −0.13 to 0.02 kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$. The minimum difference for diameter and weight occurred on 27 September and the minimum for fruit quality occurred on 20 September. By considering the fruit quality as the most important characteristic we could consider the optimal harvest time to have been 20 September.

Discussion

Apple fruit growth and storage

The considerable variation in climate factors (Table 1) affected fruit development in the cv. 'Elstar' in Denmark in relation to the number of days from full bloom to harvest and apple fruit diameter.

The average apple fruit diameter varied from 5.4 to 86.7 mm and the fruit weight varied from 62 to 265 g with an average of 150 g and the fruit quality varied from 0.03 to 1.3 kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$ (Table 2). Such variations can be considered as quite acceptable for apple fruit quality characteristics and this level of variations similar to that found when considering the soil conditions and tree vigour as described previously (Perry et al. 1987; Ingle et al. 2000).

The changes in fruit quality from ca. 0.45 at harvest to about 0.05 kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$ after 32 d storage showed a fast decrease in this quality characteristic during cold storage in normal atmosphere whereas storage showed a similar decrease after 151 d (Table 3). This is comparable to previous research (Lidster et al. 1981). On this basis it is concluded that acceptable post harvest quality of 'Elstar' in CA storage was 5 to 7 months, which was significantly longer than the 2 months when apples were cold-stored in normal atmosphere. As the climate and production factors change, it can be expected that these averages and distributions may also change significantly over the coming years.

Factor analysis and climate factors

Extraction of the 3 factors named: 1) energy and water, 2) heat wind and 3) vapour pressure deficit accounted for 47, 34 and 7 % individually and totally 88 % of the data variation. This was considered as a satisfactory result using data from plant material (Überla 1971; Sharma 1996). The fruit quality characteristics were included in the energy and water factor together with a number of factor loadings from degree days, global radiation, evaporation potential, precipitation in the morning, maximum precipitation, relative humidity, surface wetness and nineteen of their interactions had a significant effect ($P > 0.60$) on the quality characteristics (Table 4). From this it may be concluded that 47 % of the data variation is associated with quality characteristics and 41 % of the data variation is associated to other characteristics, number of cells produced immediately after pollination, the biochemical processes in the apple tree leaves.

Neither apple fruit diameter, fruit weight nor fruit quality were included in the wind and heat factor or the vapour pressure deficit factor.

Multiple linear regressions with forward selection of climate variables

According to Equation 1, apple fruit diameter significantly positively correlated to maximum precipitation (pma $rain^{-1}$) plus the evaporation potential (kep*5.9E-3) plus interaction between degree days and the difference between maximum and morning precipitation, minus the interaction between evaporation potential, plus interaction between surface wetness and precipitation in the morning, minus the interaction between global radiation and surface wetness, plus the interaction between global radiation and degree days. The regression constants for maximum precipitation and evaporation potential were considerably higher than the regression constants for the other climate factors and their interactions.

Apple fruit growth is initiated by an intensive number of cell divisions followed by a linear increase in the number of cells for 4 to 6 weeks (Bergh 1990; Lakso et al. 1995; Austin et al. 1999; Warrington et al. 1999). And thereafter growth continues with an increasing rate until the inflection point of the curve is reached where a de-

Table 6. Modelled fruit diameter, weight and quality (starch index) in 2005 using equation 1, 2 and 3 estimated using the measurements from 2004 and the climate data from 2005.

Harvest date in 2005	Diameter (mm)			Weight (g)			Fruit quality (kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$)		
	Measured	Predicted	Difference	Measured	Predicted	Difference	Measured	Predicted	Difference
30. Aug	63.3	65.0	−1.7	113	113	0	0.73	0.85	−0.13
05. Sep	65.1	66.4	−1.3	126	124	2	0.66	0.70	−0.04
13. Sep	67.5	68.2	−0.7	136	132	4	0.52	0.58	−0.06
20. Sep	68.8	69.3	−0.4	147	142	5	0.46	0.44	0.02
27. Sep	70.7	70.5	0.2	153	151	2	0.20	0.29	−0.09
04. Oct	72.1	71.3	0.8	162	156	6	0.11	0.23	−0.11

creasing growth rate occurs until the end of the growth period (Reichel and Schmidt 1989; Lakso et al. 1995). Accumulation of fresh weight including absorption of water occurs a few days after pollination (Schechter et al. 1993; Atkinson et al. 2001) and continues according to s-functions until the apple fruit maturation period (Lakso et al. 1995; Atkinson et al. 1995, 2001; Austin et al. 1999; Warrington et al. 1999). A sigmoid growth pattern of apple fruit diameter was reported previously (Reichel and Schmidt 1989; Atkinson et al. 1995; Austin et al. 1999; Warrington et al. 1999).

Growth of apple fruit mainly occurs during the night and in the early daylight morning hours. This process depends on day and night temperature, which promotes photosynthesis and transport of soluble substances from the leaves to the apples (Hansen 1977; Jones 1981), and water from the soil (Blankenship 1987; Bergh and Cloete 1992). Diurnal shrinking of apple fruit diameter was increased by low humidity, high solar irradiation and high temperature that may occur from ca. one hour after sunrise until the early morning (Blankenship 1987; Bergh and Cloete 1992). Apple fruit diameter depends on the supply of water and energy. These factors are strongly associated with evaporation from the leaves, and production, translocation and deposition of photosynthates, and water and nutrients into the apples.

According to Equation 2 apple fruit weight is linearly correlated with temperature expressed as degree days. This is in accordance with dry matter production in plants and the yield of apple in t ha^{-1}, these parameters are also linearly correlated with light interception (Monteith 1977; Palmer 1988, 1992; Campbell and Marini 1992).

Apple tree roots absorb water from the soil, and transport it through the xylem to all plant parts. In the leaves the majority of water is lost by transpiration (Raven et al. 2005). The majority of potassium is supplied through the phloem together with most of the organic carbon, nitrogen compounds and a proportion of the water (Hansen 1973; Paté 1976), whereas phosphorus, nitrogen and magnesium are translocated into the fruit together with dry matter (Tromp 1975).

Increasing light intensity increased carbohydrate accumulation, which influences fruit weight and soluble solids in the apple fruit (Greer 1995; Klages et al. 2001). The content of carbohydrates was higher in leaves with fruiting shoots than non-fruiting shoots. Accumulation of carbohydrates was greater in apples grown on fruiting shoots, where up to 80–90 % of the synthesized carbohydrates were accumulated in the apples (Hansen 1967, 1971). The amount of photosynthates produced in the leaves was correlated to light interception and these substances were translocated from near and distant leaves to the apple fruit where they are deposited as carbohydrates, carboxylic acids and other components that contribute to increases in fruit weight and soluble solids (Hansen 1967; Bergh and Cloete 1992; Klages et al. 2001). The accumulation of carbohydrates may decrease with increasing night temperature because the respiration increases (Wibbe and Blanke 1995). As biochemical processes in plants depend on temperature, research has shown a very strong and positive effect of post bloom air temperature on apple fruit weight (Perry et al. 1987; Reichel and Schmidt 1989; Bergh 1990; Lakso et al. 1995; Atkinson et al. 1998; Warrington et al. 1999; Stanley et al. 2000). Other researchers have found that increased air temperature, surface wetness, air humidity, soil temperature and a reduced evaporation potential may promote apple fruit growth (Reichel and Schmidt 1989; Corelli-Grappadelli and Lakso 2004).

According to Equation 3 the fruit quality was significantly and positively correlated to wind velocity*relative humidity and negatively correlated to wind velocity*maximum precipitation, wind velocity*global radiation, degree days and relative humidity. Wind velocity is positively related to the fruit quality, whereas the other climate variables and their interaction were negatively correlated to the fruit quality.

The linear decrease in fruit firmness during maturation (Greene and Autio 1990) was significantly related to hydrolysis of pectins (Bartley and Knee 1982).

During apple fruit development starch content increased according to a s-curve and reached maximum ca. a week before the optimum time of harvest for long-time storage cultivars (Fan et al. 1995; Magein and Leurquin 2000; Peirs et al. 2002). High temperatures during the last part of the growth season may result in an earlier maturation (Smith et al. 1979; Watkins et al. 1982). These changes are taken into consideration via the starch index, Streif index, which represents apple fruit maturation and therefore was included in determinations of fruit quality (Streif 1983, 1996; Drake and Kuppferman 2000).

The heat and wind factor accounted for 34 % of the data variation and the vapour pressure deficit factor accounted for 7 % of the data variation, these were not significantly related to the fruit quality, fruit diameter or weight. The heat and wind factor had loadings above 0.90 from soil temperature, wind velocity and 15 interactions that were non-significantly associated with apple fruit diameter, weight or fruit quality. Therefore, other physical processes such as uptake of water, transport of nutrients and transpiration of water are likely to be critical factors involved in apple fruit growth and development. The vapour pressure factor accounted for 7 % of the data variation and this was influenced by several interactions, degree days and vapour pressure deficit, precipitation in the morning and vapour pressure deficit, relative humidity and vapour pressure deficit and vapour pressure deficit, global radiation, degree days*vapour pressure deficit, precipitation in the morning*vapour pressure deficit, relative velocity*vapour pressure deficit and vapour pressure deficit*global radiation). Therefore the vapour pressure factor provides a measure of the effect of vapour pressure deficit which promotes transpiration without influencing fruit diameter, weight and fruit quality.

Effects of storage on apple fruit quality

The rate of change in fruit quality during normal atmosphere cold storage and CA storage showed that optimization of the harvest time resulted in a considerable delay in the reduction of fruit quality during storage (Table 3). Previous research has shown that use of maturity indices to determine optimal harvest date resulted in an improvement of the apple fruit quality after storage (Streif 1983, 1996).

Validation of the statistical models

Results from prediction of fruit diameter, fruit weight and fruit quality in 2005, using the models generated from

data from 2002 to 2004, are presented in Table 6. The differences between measured and modelled apple fruit diameter using degree days varied from −1.7 to 0.8 mm a difference of 0.2 mm at harvest time, on 27 September. For fruit weight the differences between measured and predicted values varied from 0 to 6 g; fruit quality varied from −0.13 to 0.02 kg cm^{-2}w/w $\%^{-1}$ $scores^{-1}$ with a minimum difference on 20 September. The minimum difference for diameter, weight and fruit quality occurred between 20 and 27, on 29 and on 21 September, respectively. According to the differences for diameter and weight the optimum harvest time was the 28 September. By considering the fruit quality as the most important characteristic the optimum harvest time should have been between 21 and 28 September, in 2005.

These results show the potential of the models for predicting these three quality characteristics (Table 6). Similar results were obtained using evaporation potential, relative humidity, global radiation and surface wetness. Several studies have shown that apple fruit growth based on fruit diameter may be modelled using temperature (Perry et al. 1987). Previous research has also shown that fruit quality (Lakso et al. 1995; De Jäger and Roelofs 1996; Peirs et al. 2002) and diameter (Ortega-Farías et al. 2002) may be modelled using degree days. On the basis of these results it is concluded that apple fruit diameter, fruit weight and fruit quality may be predicted using Equation 1, 2 and 3, respectively.

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